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A BARENTS SEA FISH RESOURCES AND MIGRATION MODEL

DEVELOPED WITH SPECIAL REFERENCE TO OIL ACTIVITY

By

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ABSTRACT

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A model is developed on the basis of distributions of fish resources and temperatures observed during surveys in the Barents Sea over the period 1983–1987. It is found to be useful (although not detailed enough, due to lack of data) for predicting fish migrations at least two to three months ahead of the last survey.

This might, for instance, be of great interest for predicting contacts between fish stocks and oil slicks in scenarios of possible oil pollution in the Barents Sea.

The model is based on general knowledge of seasonal fish migration modified by seasonal variations in average sea temperature at 50–200 m depth.

It is postulated that the fish migrate towards a "preference" temperature, either directly, in order to satisfy metabolic requirements, or indirectly, as when attracted by concentrations of food organisms. The highest "preference" temperature, 5.5°C, is estimated for southwards winter migration of mature cod and haddock (e.g. to the spawning grounds in the Lofoten–Vesterålen area).

For mature capelin 3.5°C seems to be the "preference" temperature in the model for southwards winter migration (mainly towards the spawning grounds near Finnmark).

During summer the older cod and haddock, preferring the higher temperatures, migrate a shorter distance northwards to feed than do the younger mature and the immature fish of these species.

In the model 5.5°C is, therefore, used as the "preference" temperature for the northeastwards summer migration of old cod and haddock, while 3.0°C is applied as the best "feeding migration" temperature during the same period for younger fish of these species.

As capelin in summer may live far north of cod and haddock, the "preference" temperature for northwards summer migration is expected to be lower than for cod and haddock.

In the model 1°C is used as the "preference" temperature for "feeding migration" of immature capelin.

INTRODUCTION

The Barents Sea is a relatively shallow continental shelf area with an average depth of about 230 m (Zenkewitch, 1963). It is about 1.4 i 10^6 km^2, limited in the west by the slope down to the Norwegian Sea, in the east by Novaya Zemlya, and in the south by the USSR and the Norwegian mainland. In the north, the borderline with the Arctic Sea may be drawn between the islands Spitsbergen, Kvitøya, Victoria- and Franz Josef Land. In

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late summer the whole area may be free of ice, while in cold years the minimum ice extension may reach a line between southern Spitsbergen and northern Novaya Zemlya. In mild winters the maximum ice distribution covers a similar area as in cold summers, while in cold winters the ice may cover the sea south of Bear Island in the west. East of 40° E the ice may cover the whole area south to the USSR mainland.

In the southwest, there is an inflow of Atlantic water with a salinity higher than 35 parts per thousand and a temperature about 5°C. Water in the Norwegian Coastal Current, characterized by lower salinity, also flows into the Barents Sea. Both water masses are rich in nutrients and add to the fecundity of the sea. Likewise in the northern parts, Arctic water with a salinity below 35 ppt and temperatures mostly below 0°C (except in the upper 10–20 m during summer), flows into the area. Naturally there is a comparable flow of water out of the Barents Sea, for instance as cold bottom water westwards through the Bear Island Channel, and as a northeastward current in the deeper layers between Franz Josef Land and Novaya Zemlya.

The primary productivity of the area is dependent on the amount of mineral nutrients available. In spring the upper nutrient rich, stable and cold melt-water may sustain a strong primary production (Rey and Loeng, 1985; Skjoldal *et al.*, 1987). In cold years larger areas are influenced by melt-water than in milder years. While the low temperatures do not limit phytoplankton growth with good light conditions, zooplankton production may be inhibited (Ellertsen *et al.*, 1982; Rey *et al.*, 1987a). During winter the zooplankton is mainly concentrated in deeper sea layers, migrating to the upper layers in early spring for feeding and reproduction. In mild springs most of the produced phytoplankton may be consumed by the next link in the food chain (Rey *et al.*, 1987a). This may not be the case in cold early springs, when the short generation time of phytoplankton can cause the early bloom to die off and the phytoplankton to sink, thus becoming less available to the slower growing zooplankton (Rey *et al.*, 1987b). The spring phytoplankton bloom generally utilizes most of the available mineral nutrients in the upper layer, whereafter the production is markedly reduced.

The most important fish populations of capelin, northeast Arctic cod, haddock, saithe and redfish, which use the Barents Sea, the Svalbard area and the northern part of the Norwegian Sea as nursery and feeding areas, also use the Norwegian coastal waters for reproduction. Dragesund and Gjøsæter (1988) and Loeng (1989) have reviewed knowledge of the Barents Sea as an ecological system. The two papers emphasize, respectively, the fish biology and abiotic factors. The abundance of fish in the Barents Sea is dependent on the southwards spawning migrations, and the subsequent transportation of spawning products by the prevailing currents back to the nursery and feeding grounds. The success of the processes is closely connected with the envi-

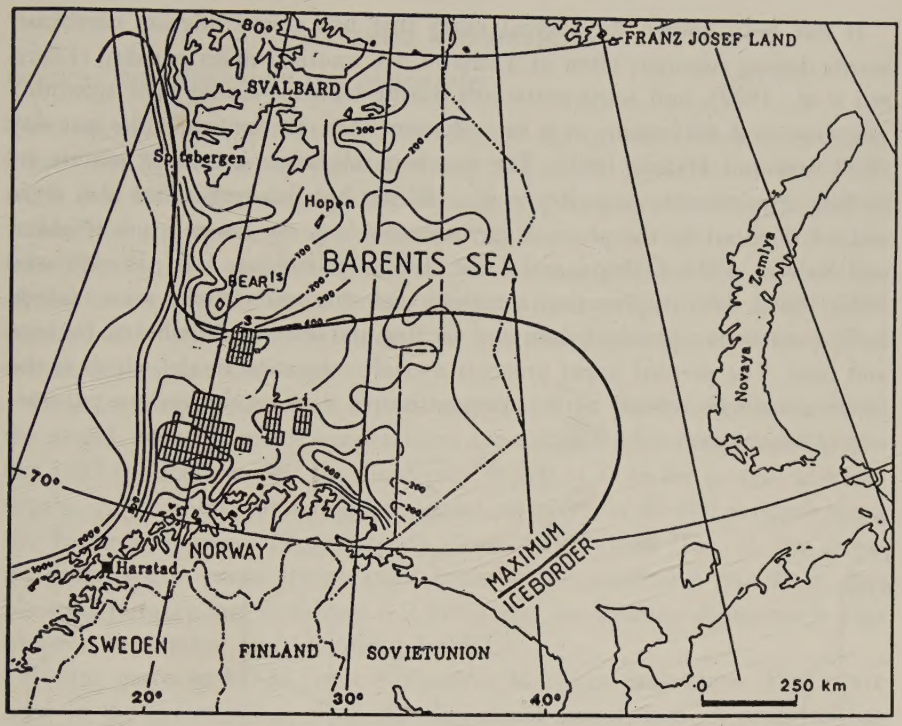

Fig. 1. The Barents Sea with depth contours and maximum ice limits. "Blocks" opened for drilling in 1988 in the Norwegian zone are included. (Redrawn from Lindseth, 1987).

ronmental conditions of the water bodies. Man may influence these processes by his activities, for example, by oil exploration with attendant risk of "blow outs" and heavy oil pollution.

For this reason environmental impact studies are required in advance of oil exploration. In 1988 a few non-commercial drilling efforts have been approved on so-called "strategical oil blocks" in the southern parts of the Barents Sea (Fig. 1). An impact statement on the effects on fish resources in this area has been presented by the Norwegian Ministry of Petroleum and Energy (Børresen *et al.*, 1988), based on preliminary reports by Føyn (in prep.), Wielgolaski (1987), Melle and Skjoldal (1987) and by Serigstad et al,. (1987) (all in Norwegian with brief English summaries). Results from the Norwegian Marine Pollution Research and Monitoring Programme are presented in booklets by FOH (1983; 1984, the last one in Norwegian only). All papers indicate that both fish and zooplankton may be harmed by oil pollution, particularly during the reproductive phases. The damage may be strong, especially on eggs and drifting young larvae of both zooplankton and fish.

It has been known for several years that fish stocks migrate northeastwards during summer, often at a rate of 3–6 nautical miles per day (Ellertsen *et al.*, 1982), and southwestwards during winter. During their spawning migration cod may swim at a rate of more than 10 nautical miles per day (Rollefsen and Hylen, 1981). The summer migration is caused mainly by feeding requirements (e.g. Rey *et al.*, 1987a), but fish migrations also seem to be influenced by the physical environment, e.g. the temperature (Nakken and Raknes, 1984; Ozhigin and Luka, 1985; Tjelmeland, 1987; Wielgolaski, 1987; 1988). This implies that a realistic fish migration model must include both quantitative physical data and feeding parameters distributed by area and time. The present paper presents a crude migration model which in the future should be refined by better quantitative data on the various parameters of importance.

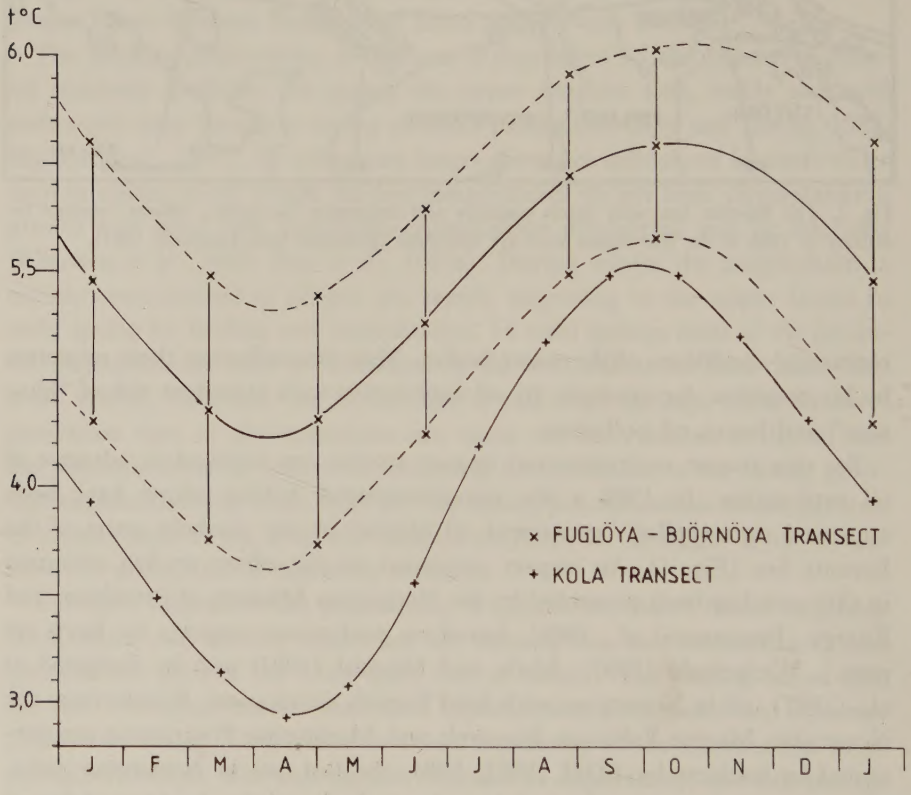

Fig. 2. Calculated average temperatures in degrees Celsius at 50–200 m depth for various months along the Fugløya-Bjørnøya (Bear Island) transect of the Barents Sea in the period 1977–1986 (dotted lines indicate the standard deviation), and for the Kola transect at 0–200 m depth in the period 1921–1980 (H. Loeng, pers. comm.).

MATERIAL AND METHODS

PHYSICAL OCEANOGRAPHY AND GEOGRAPHY

Currents are important to fish migration in many ways. They directly influence the northeastward drifting of eggs and young larvae in summer. Indirectly they influence fish migration through, for instance, the fecundity of the waters and the presence of planktonic organisms important as food for the fish. The currents and the salinity of the Barents Sea, however, are not included in the model. These factors interact, however, with the temperature conditions, which are often found to be correlated with the variation of fish resources in space and time.

Data on temperature from several surveys of the Barents Sea are used in the model. Monthly mean temperatures are calculated for the period September 1983 to October 1987 for the depth 50–200 m or to the bottom at lesser depths. According to an average temperature curve for 50–200 m depth along the Fugløya–Bjørnøya (Bear Island) transect 1977–1986 (Fig. 2), the greatest difference in mean temperature between two successive months is that between January and February (–0.35°C) and the smallest difference is that between September and October (+0.06°C).

Isoline maps on UTM (zone 35) and/or Mercator projections (Fig. 3) are used in the presentation of all the digitalized stored data. A program has however, been developed in a separate project to present computerdrawn maps in the various projections (Westgaard *et al.*, 1988). In the present model all data from the Barents Sea are calculated for areas of 1° longitude and 15′ latitude. The data are given in a 100 by 80 matrix (40°W – 60°E and 60°N – 80°N).

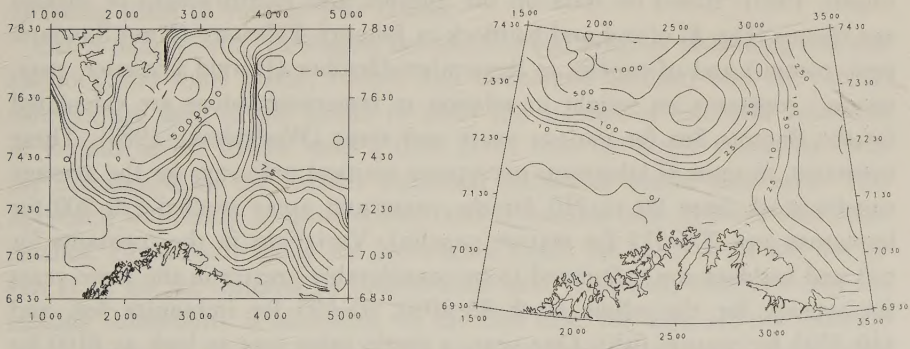

Fig. 3. Left. Map in Mercator projection for a large sector of the Barents Sea. Isolines of total capelin resources in September–December 1983 given in 10 kg per square nautical mile. Right. Map in UTM projection for a relatively small sector of the Barents Sea. Isolines of young capelin resources in September 1983 in 10 kg per square nautical mile.

BIOLOGICAL RESOURCES AND FISH CATCHES

The relative abundance of the resources in the sea are estimated acoustically by echo sounders coupled with integrators. The integrated echoes from various depth intervals are related to the amount of biological resources. Fish species are identified from the echograms on the basis of experience, but are also checked by fish catches at trawl stations (Fig. 4). The acoustic frequency used for fish recordings was 38 kHz. The recorded values are manually divided among the different species and are presented as integrated amounts per square nautical mile within each depth interval. The model software transforms these data to a mean value for each area or box given by the 100 by 80 matrix, each value based on one or several surveys. The distance between the tracks of the research ships may, however, be considerably longer than the distances given by the box areas of the matrix. This means that the matrix often has to be smoothed (averaged) between neighbouring areas. In most cases this is preferable for construction of isoline maps, but it may in some cases give a misleading impression of the distribution of a fish population. All the values in the average matrix are weighed by the distance in nautical miles from the center of each box of the matrix.

There are very few quantitative data available on the various plankton species for comparison with 38 kHz integrator values. The term "plankton" in the model, therefore reflects a very heterogeneous group, including small fish larvae, greater zooplankton organisms (as for instance krill), and also some smaller plankton species. The smallest zooplankton and phytoplankton, however, are probably not significantly observed with the echo sounders using 38 kHz.

To compare fish abundances based on echo integrator values with catch data, the acoustic indices were transformed to weight (Dommasnes and Røttingen, 1985). Based on data on the number and length/weight of various age classes (Fig. 4) of cod and haddock in January–February (Knut Sunnanå pers. comm.) and of capelin in September–October (Harald Gjøsæter, pers. comm.) constants on weight in relation to integrator values are calculated for the Barents Sea for various years and areas (Wielgolaski, 1988). These constants, in units of kilograms per square nautical mile vary for the average capelin stock from 90 to 210 for the years and areas studied (70–200 for immature and 200–515 for mature capelin). Variations in the constants for cod and haddock are calculated to be considerably greater in the same years (in average for the whole stock 85–1030, 65–595 for immature fish and 440–3505 for mature fish). One year, a single value was as high as 8160 for mature fish of these species in the most eastern area of the Barents Sea, probably due to the very few detected specimens. Only rough estimates of the weight of fish resources are possible by this method, as the constants are

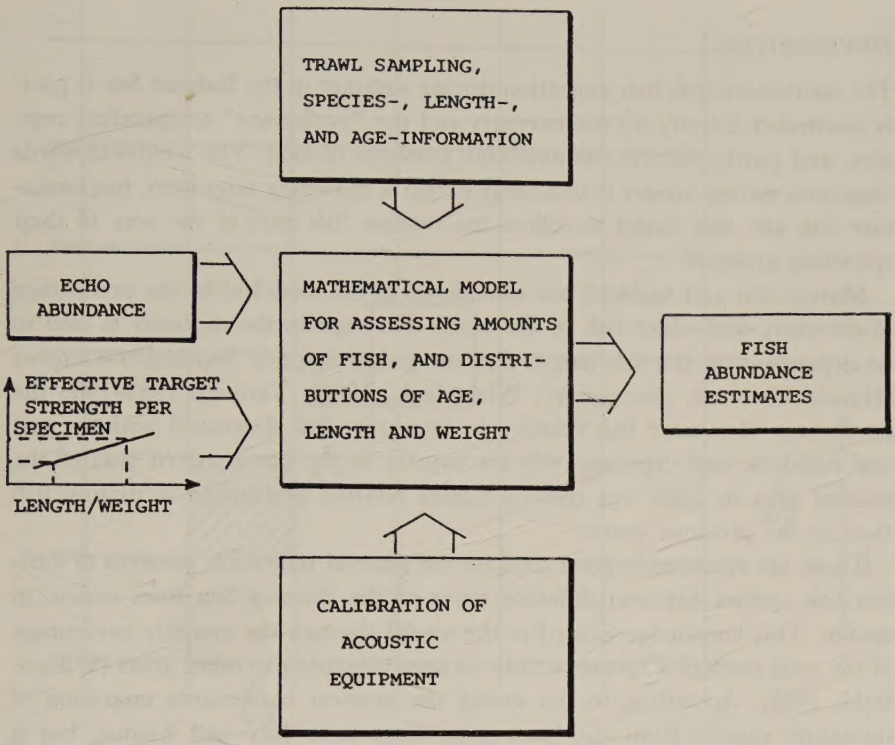

Fig. 4. The processes of the extended acoustic method for fish abundance estimation (Dalen and Smedstad, 1983).

calculated only once a year and for larger areas of the Barents Sea. There are also uncertainties in dividing the integrator values by species and in ascribing them to various year classes.

Catch data for the Norwegian Barents Sea cod fisheries (including cod and haddock and some saithe, redfish and Greenland halibut) and the capelin fisheries are used in the model to study the amount of catchable resources in various areas. In the model, data given only for larger statistical areas are distributed on the smaller statistical rectangles within each area. This approach will rarely be quite correct and is possible only in areas with trawl catches. Particularly along the Norwegian coast, the catch areas are not given at all for the fisheries by conventional gear (Oppedal, 1987), or only the landing community is identified. In the first case, the data are not included in the model. In the second case, the catches are allocated to the most reasonable statistical rectangles. All data for the statistical areas and the smaller rectangles of various sizes, are recalculated on an area basis, and placed in the relevant boxes in the matrices.

FISH MIGRATION

The northeastwards fish migration during summer in the Barents Sea is partly controlled directly by the currents and the "preference" temperature regimes, and partly also by the available amounts of food. The southwestwards migration during winter is to a large extent a spawning migration, but immature fish are also found to follow the mature fish part of the way to their spawning grounds.

Mature cod and haddock are considered in the model to be the percentage of six–years–and–older fish in the stock. For capelin the maturity is said to be dependent on the fish length and the gonad stage in September–October (Harald Gjøsæter, pers.comm.; Wielgolaski, 1988). Through 1983–1986 the percentage of mature fish relative to immature fish decreased both for cod and haddock and capelin. Only for capelin in the northeastern part of the studied area in 1986 was there a higher relative percentage of mature fish than in the previous years.

There are reasonably good data on the general migration patterns of various fish species between different areas of the Barents Sea from season to season. This knowledge is used in the model through the monthly percentage of the total stock of a species within an area migrating to other areas (Wielgolaski, 1988). According to the model the greatest northwards migration of immature capelin from the Norwegian coast is in July and August, but it continues at a lower rate in September and October as well. In September–October it is also supposed that there is some northwards "feeding migration" of mature capelin. According to the model, the general spawning migration of this species southwards towards the northern coast of Norway and the Murman coast takes place from January to June. The migration of cod and haddock between various areas may take place over a longer period of the year than that for capelin. Immature cod and haddock migrate northwards mainly in July, but this migration is supposed to start in April and last until September. According to the model, mature cod and haddock also migrate northwards in the same period, but with the largest migration occurring in September. The strongest southwards migration both of mature and immature cod and haddock is expected to take place in March, but starting already in October, particularly for mature fish.

The principles of the migration model are most easily shown by a general example. Figure 5 shows part of the 100 × 80 matrix that covers the respective ranges of longitude from 40°W to 60°E and of latitude from 60°N to 80°N. The subdivision of this area is uniform with respect to the geographical coordinates. Thus each square in the figure represents 1° of longitude and 15′ of latitude. The area of a single square is approximated very well by the

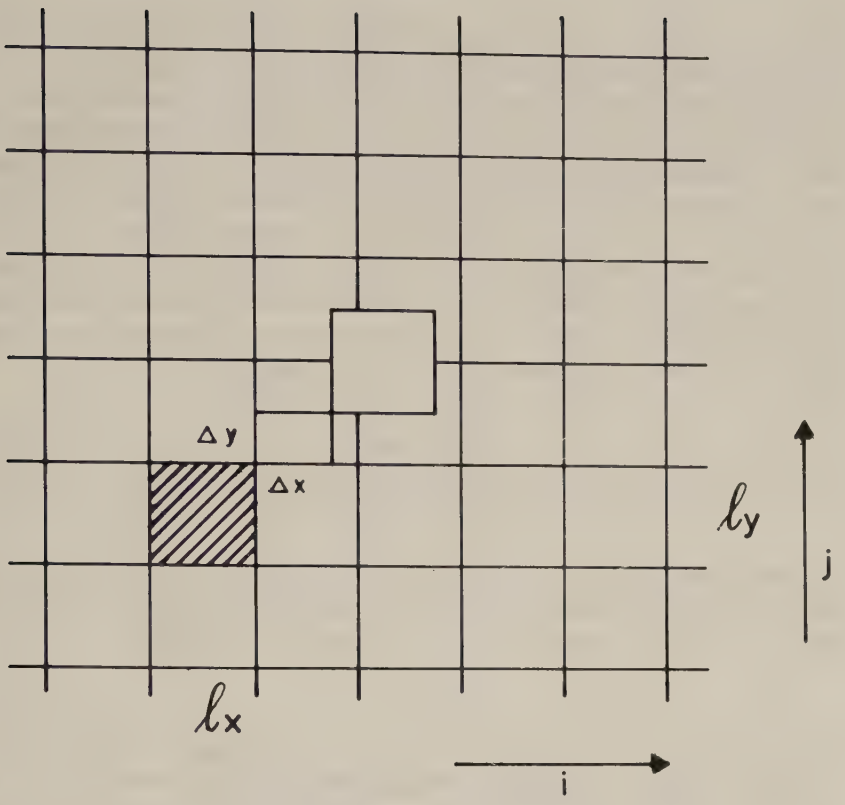

Fig. 5. Some squares in the 100 by 80 data matrix of the Barents Sea area. Further explanation in the text.

product $l_x l_y$, where $l_x = (2\,\pi\,R/360)\cos\beta$, R = 01.27 10^7/1852 nautical miles is the radius of the earth, β is the latitude, and l_y = 15 nautical miles.

To illustrate the workings of the model, through Fig. 5, all of the fish is assumed initially to be concentrated in the shaded box. In time Δt, 100% of the fish quantity is assumed to migrate the distance Δx in the longitudinal or east-west direction and Δy in the latitudinal or north-south direction. In terms of the migration rate (V_x, V_y), $\Delta x = V_x \Delta t$ and $\Delta y = V_y \Delta t$. The sign convention is that x is positive in the easterly direction and y is positive in the northerly direction, hence for V_x and V_y too. In the particular case of Fig. 5, the fish are distributed over four squares or cells of the matrix after time Δt. Other possibilities in the considered special case of migration of 100% of the initial fish quantity are that the resulting distribution occurs over two cells or one cell. In the general case, some percentage of the initial amount will be distributed over one, two, or four cells after migration, while the complementary percentage will remain in the original cell after time Δt.

The amount of fish in each of the covered cells after Δt is found by multiplying the fractional area containing fish in each cell by the original amount of fish, making proper allowance for the migrating and stationary parts.

Given an initial distribution of fish over one or more cells, the migration process is performed independently with respect to each cell for the same incremental time period Δt. The individual results are combined to describe the new fish distribution. This process may be repeated n times.

The migration model exists in two distinct forms. These are distinguished by the neglect of or explicit inclusion of environmental factors. In the first model form, the migration rate for those fish that are migrating a particular time depends only on the coordinates x and y and time t:

$$V_x = V_{xo}(x,y,t), \tag{1a}$$

and

$$V_y = V_{yo}(x,y,t), \tag{1b}$$

The percentage of adult fish or young fish that begin migrating from a given place at a given time will, in general, vary, hence is also described as a function of x, y, and t. In terms of the area density ϱ,

$$\varrho_s = \varrho_s(x,y,t), \tag{2}$$

where the subscript distinguishes between adult fish and young fish, whose distributions are generally different. In numerical computations, these forms are taken from historical data, consisting of long-term trends expressed by averages over rather long periods of time. Without allowance being made for climatic factors, however, the first model form often gives unsatisfactory results.

A step towards an environmentally governed migration model is taken in the second model form. In this, the migration rate is composed of two terms, one representing the long-term trend, as in equation (1), and the other containing a temperature-dependent term. Mathematically,

$$V_x = V_{xo}(x,y,t) + V_{xT}(x,y,T), \tag{3a}$$

and

$$V_y = V_{yo}(x,y,t) + V_{yT}(x,y,T) \tag{3b}$$

where the temperature-dependent term is denoted by the symbol T. Time is also included implicitly in the second terms V_{xT} and V_{yT} through the temperature field $T = T(x,y,t)$. This and the postulated "preference" temperature T_o drive the environmental part of the model. As before, the percentages of

adult fish and young fish that begin migrating from a given place at a given time are described by distinct functional forms, specifically those given in equation (2). The temperature-driven migration rate (V_{xT}, V_{yT}) is proportional to the deviation in local temperature $T(x,y,t)$ from T_o, and the direction is determined by the local temperature gradient, which is described by the direction cosines R_x/R and R_y/R. In particular,

$$V_{xT} = K \mid T_o - T\ (x,y,t) \mid R_x/R, \tag{4a}$$

and

$$V_{yT} = K \mid T_o - T\ (x,y,t) \mid R_y/R, \tag{4a}$$

where K is the migration rate constant, and R_x and R_y are the so-called indicators of east-west and north-south migration, respectively, with $R = (R_x^2 + R_y^2)^{\frac{1}{2}}$. The indicators are given by the equations

$$R_x = [T_o - T(x,y,t)]\ G_x, \tag{5a}$$

and

$$R_y = [T_o - T(x,y,t)]\ G_y, \tag{5b}$$

where G_x and G_y are the temperature gradients in the east-west and north-south directions, respectively. These last quantities are estimated locally by computing the temperature differences between adjacent matrix cells and dividing these by the corresponding lengths l_x and l_y, shown in Fig. 5, hence

$$G_x = [T(x+l_x,y,t) - T\ (x,y,t)]/l_x, \tag{6a}$$

and

$$G_y = [T(x,y+l_y,t) - T\ (x,y,t)]/l_y. \tag{6b}$$

While the migration process is conducted purely mathematically, the constants of geographical boundaries, namely land masses, are respected. Migration thus ceases at coasts.

A particular modelling exercise is executed in the following manner. The starting time is defined by the time of a survey. The initial fish distribution is defined by the echo integrator values summed over each cell of the 100 ×80 matrix. The migration process is simulated according to the above equations in time increments $\Delta t = 1$ day over the total time period of interest. This might be two months, for instance.

To judge the quality of the model, the resulting distribution is compared with that due to a second survey performed at the end of the examined time period. A difference measure D is computed by summing the squares of deviations between the predicted and observed distributions, namely

$$D = \sum_{i=1}^{100} \sum_{j=1}^{80} (M_{ij} - \hat{M}_{ij})^2, \qquad (7)$$

where M_{ij} is the measured echo integrator value pertaining to the (i,j)-cell and $\hat{M}_{ij}$ is the corresponding estimated value. Since the "preference" temperature is unknown, the model is exercised systematically over a range of values of T_o. The value giving the lowest of minimum value for D defines the "preference" temperature.

The final migration rates and directions in the model are found by summing the several quantities due, respectively, to the general migration between areas and to the temperature-driven migration. The summation is a running operation, being performed at the end of each time step Δt. Allowance is made for the generally irregular or asynchronous onset of migration in both adult fish and young fish, as indicated by equation (2).

For general forecasting, the "preference" temperatures found for specific stocks by the kind of modelling exercises described here would be used. Sea temperatures are then predicted to deviate from a "normal" temperature in the same way as they deviated at the time of the last available survey (Fig. 2). It seems that this is a useful method, at least for predicting fish migration two or so months in advance.

RESULTS AND DISCUSSION

The average temperature in 50–200 m depth in the Barents Sea generally decreased during the studied 1983–1987 period (Fig. 6).

The tendency of decreasing temperatures during the years of study may have influenced both the feeding migration and the spawning migration, and has probably also reduced the growth rate of the fish (Loeng, 1989).

BIOLOGICAL RESOURCES AND FISH CATCHES

1) *Plankton*

The biomass of zooplankton is influenced by fish consumption, in the Barents Sea particularly by capelin, as well as by their own growth and reproduction (Skjoldal *et al.*, 1987). The population of capelin strongly decreased during the 1980's, and this may, therefore, be an important reason for the relatively high echo integrator values of "plankton" recorded on average for the years 1983–1987. During January–April this was true east and southeast of Spitsbergen and northeast of the Varanger Peninsula (Fig. 7, left). Particularly during the first years of the study period the relatively higher sea temperatures may also have been favourable for early zooplankton reproduction and growth.

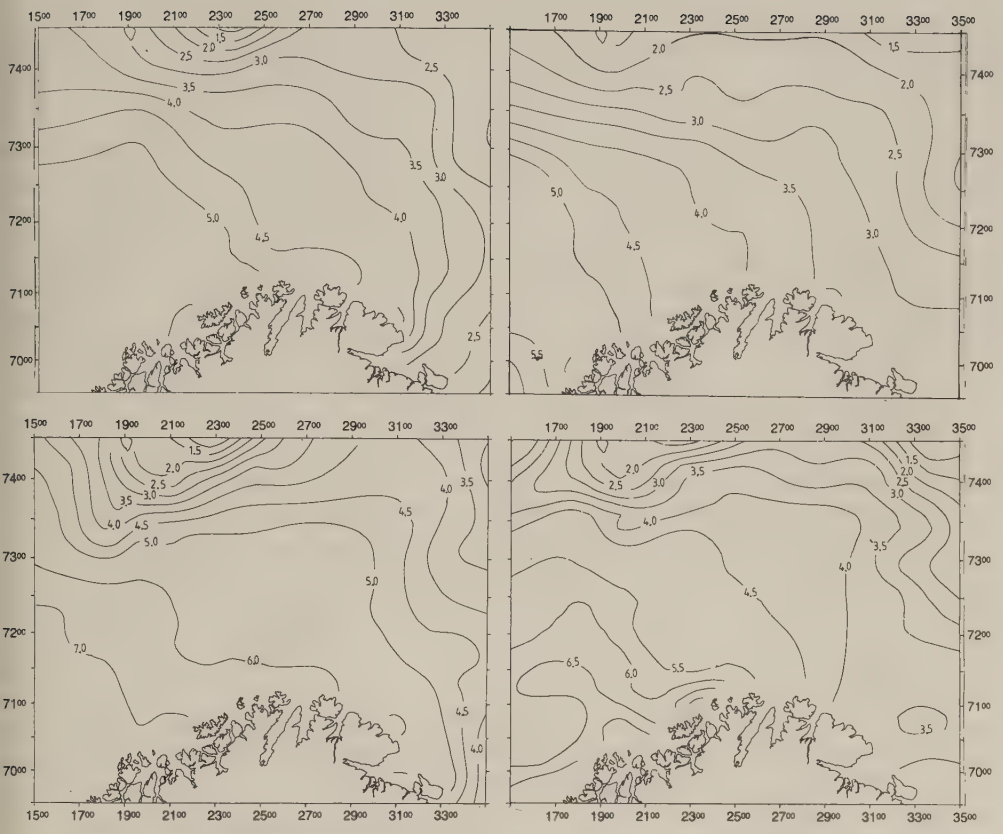

Fig. 6. Average sea temperatures at 50–200 m depth in the southern Barents Sea in May (top) and October (bottom). Left, 1984. Right, 1987.

During May–August, a large "planktonic" mass is still observed just south of Spitsbergen (Fig. 7, middle). In this area there is little *Calanus*, while larvae of *Balanus* dominate (Rey, pers.comm.). The "plankton" concentration to the southwest on the same figure may be due to both zooplankton and fish eggs mixed with larvae. However, Russian investigations, in particular, have recorded the largest zooplankton biomass in the Barents Sea during June–July and especially within the geographical area 70–74°N and 10–20°E (Bliznichenko *et al.*, 1984; Degtereva *et al.*, 1986; Drobysheva *et al.*, 1988).

On the average "plankton" integrator value map for the period September–December (Fig. 7. right) there are high values in the south of the Barents Sea, both north and east of the Varanger Peninsula. The reason for this may be an increased amount of larger zooplankton due to smaller predating capelin populations, or that 0-group fish may have been included as "plankton" in the integrator values. This shows the importance of more detailed studies and subdivisions of the integrator "plankton" on the surveys. On the other

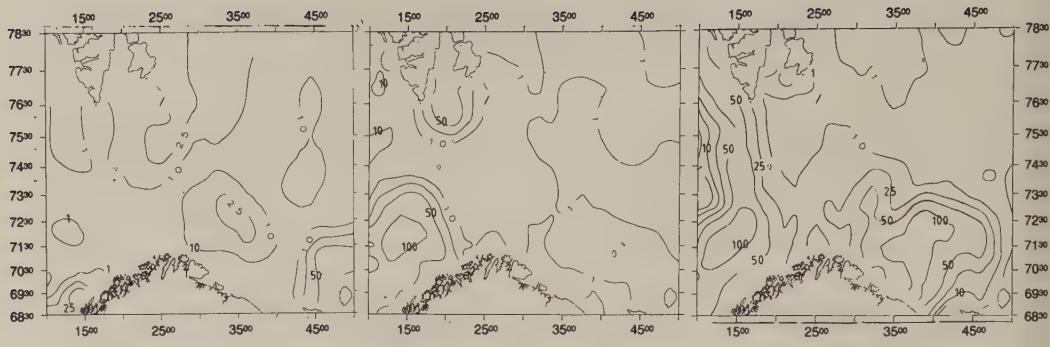

Fig. 7. Integrator values of "plankton" in the Barents Sea, average 1983–1987. Left, January–April. Middle, May–August. Right, September–October.

hand the "plankton" maps in Fig. 7 give a gross overview of geographical concentrations of small organisms, directly or indirectly sensitive to oil pollution. They seem to be of great importance, for instance, within the area from 70° to 72°N and from 10° to 20°E from May onwards.

2) *Capelin*

In 1977 the Norwegian capelin winter fisheries were good over large areas of the southern Barents Sea (Fig. 8 upper left), especially along the coast of eastern Finnmark (Oppedal, 1977). Similarly, good catches were also obtained in 1976 and 1978 (Table 1), when an easterly spawning migration of capelin towards the coast occurred. In more recent years of the study period, more of the winter catches have been made further to the west, particularly in 1983, but from the mid 1980's the catches have been strongly reduced due to the very limited stocks of capelin (Fig. 8, lower left). As expected there seems to be good agreement between the available stocks and the Norwegian catches of capelin through the studied years. This is illustrated in Fig. 8, right, for the period January–April 1984. During this period there was a strong westerly spawning migration towards the coast of northern Troms (Fig. 8, lower right). Also, that year considerable spawning migration took place towards the coast of western Finnmark, just northwest of North Cape, resulting in good catches there (Oppedal 1987).

From the figures for annual catches of capelin 1976–1986, given in the ICES Statistical Bulletins for the northern areas (Table 1), it is seen that for many years the Norwegian capelin catches constituted more than half of the total catches of capelin in the Barents Sea. From the values given in Fig. 8 (right), it seems reasonable to assume that very small capelin stocks were left for spawning after the winter fisheries in 1984. Traditionally, the fisheries are concentrated at a rather short distance from land, but with reduced

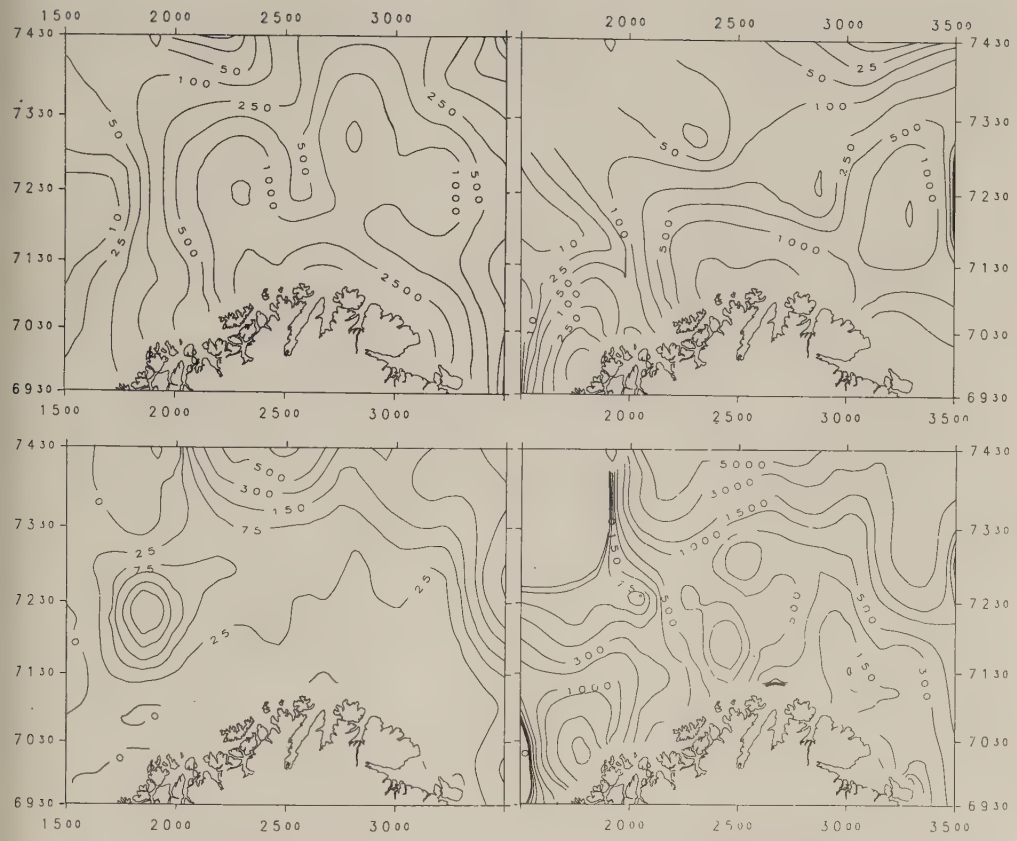

Fig. 8. Isolines for the amount of capelin (in 10 kg per square nautical mile) in the southern part of the Barents Sea during the period January–April. Upper part: Catches by Norway. Left, 1977. Right, 1984. Lower part: Resources calculated. Right 1984. Left, 1986. The two figures to the right are comparable. In the southern part of the Barents Sea, where the Norwegian capelin winter fisheries mostly take place, there is good agreement between the available resources and the catches.

resources, for instance in 1985, the limited Norwegian capelin catches seemed to be concentrated further north (Wielgolaski, 1988), and only a very weak migration towards the coast occurred. Such catches, of course, also severely reduce the still immature capelin resources.

While the capelin winter fisheries may be important in the southern Barents Sea in years with good spawning migration towards the coast, the capelin summer fisheries from August to November are concentrated in areas with good feeding conditions, often north of 74°30′N (north of the Bear Island). Such a northerly distribution of capelin occurred in 1977 and 1978, to some degree also in 1981, while the stocks from 1985 were so small even north of 74°30′N that the fisheries were minimal. However, in years with more easterly and southerly summer distribution of capelin (Oppedal, 1987),

	1976			1977			1978			1979			1980			1981			1982			1983			1984			1985			1986	
Cod	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.	Bar.	Norw.	Spitz.
Norway	156	220	10	158	262	9	128	266	4	85	240	0	72	200	0	62	265	0	68	259	0	41	230	0	44	219	2	55	181	2	85	168	5
USSR	289	2	52	293	26	51	253	10	4	102	15	3	90	19	6	62	19	2	18	7	16	7	8	8	9	4	10	56	5	2	68	47	36
Others	97	39	43	58	37	51	30	28	9	15	18	7	12	14	6	9	14	0	10	11	15	10	8	16	3	10	11	4	15	16	1	8	13
Sum	542	261	105	509	325	111	411	304	17	202	274	10	174	233	12	133	298	2	96	277	31	58	246	24	56	233	23	115	201	20	154	223	54
Tot.sum		908			945			732			486			419			433			404			328			312			336			431	
Haddock																																	
Norway	30	21	1	23	19	1	21	20	0	33	39	0	33	34	0	25	39	0	15	29	0	6	17	0	3	15	0	7	14	0	26	27	0
USSR	41	0	1	41	3	7	45	0	0	25	1	0	19	2	0	10	3	1	3	0	0	0	0	0	1	1	0	23	0	0	43	2	0
Other	24	17	4	7	9	2	3	8	0	3	7	0	1	3	0	0	4	0	0	2	0	0	1	0	0	1	0	0	1	0	0	1	0
Sum	95	38	6	71	31	10	69	28	1	61	47	1	53	39	0	35	46	1	18	31	0	6	18	0	4	17	0	30	15	0	69	30	1
Tot.sum		139			112			98			109			92			82			49			24			21			45			100	
Capelin																																	
Norway	1362	156	430	1418	317	381	859	142	259	411	189	554	299	312	433	434	585	328	421	145	586	249	506	738	200	244	474	232	102	118	72	73	0
USSR	506	1	90	699	0	122	507	0	240	451	3	216	445	0	196	665	0	47	428	13	156	311	177	358	283	29	316	277	15	106	51	0	1
Others	0	1	0	0	2	0	8	5	16	1	4	0	4	4	0	13	24	7	6	2	31	3	10	23	3	39	0	3	14	0	0	0	0
Sum	1868	158	520	2117	319	503	1374	147	515	863	196	770	448	316	629	1112	609	382	855	160	773	563	693	1119	486	312	790	512	131	224	123	73	1
Tot.sum		2546			2939			2036			1829			1393			2103			1788			2375			1588			867			197	

Table 1. Nominal catches in 1000 t of cod and haddock and capelin in 1976–1986 by Norway, USSR and other countries in the Barents Sea (Bar.), the Norwegian Sea (Norw.) and in the Spitzbergen–Bear Island area (Spitz.) (From ICES 1979–1989. Tables 5. Bull. Stat. Peches Mar. vols 61–71).

for instance in the late summer of 1983 (Fig. 3, left), a considerable Norwegian summer fishery of capelin took place south of 74°30′N, even south of 72°N.

3) *Cod and haddock*

During the late 1970's and the first years of the 1980's the cod fisheries decreased, due to reduced stocks (Table 1). In the middle of the 1980's the fisheries temporarily increased somewhat again, but probably less than they would have at higher stock levels and with a better food supply of herring and capelin. The most important area for the Norwegian cod fisheries in the southern Barents Sea is along the northern coast of the country and, in periods, also somewhat further northeast, as well as at "Sørbakken" south of the Bear Island. This is the conclusion both of Oppedal (1987) and from the digitized isoline maps presented in Figs. 9 and 10, indicating that the pre-

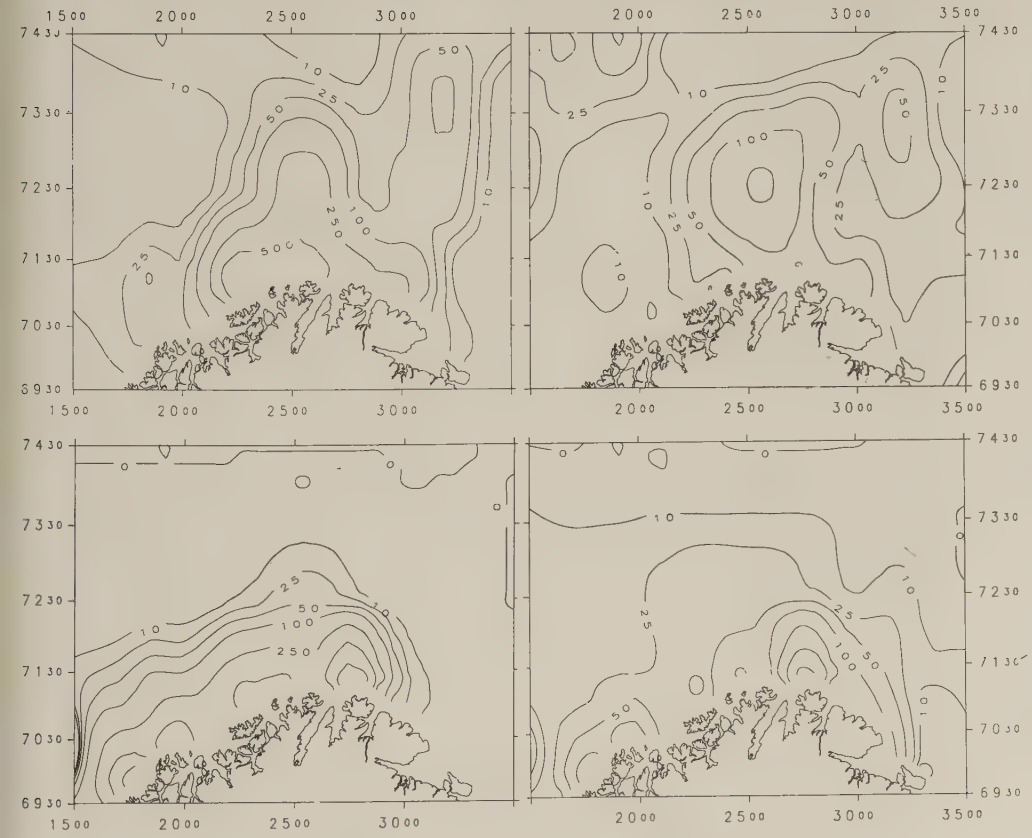

Fig. 9. Isolines for the catches in the cod fisheries (in 10 kg per square nautical mile) in the southern part of the Barents Sea. Upper part, 1976, lower part, 1981. Left, January–April. Right, September–December.

sent model realistically visualizes the situation with the available data, in spite of the necessary smoothing in the maps and other corrections made for catches with conventional gear near the coast.

Locally, there seem to be displacements of the most important cod fishing areas in the Barents Sea through the years of study. In the winter months of 1976 the Norwegian cod fisheries were of considerable significance at about 72°30′N and 25°E and at about 73°30′N and 32°E, and to some degree also in the autumn of the same year (Fig. 9, top). However, even in that year, the Norwegian winter catches of cod north of 69°30′N were highest near the coast, particularly near the coast of western Finnmark. The easterly fisheries in 1976, relatively far from the coast, may be caused by an easterly distribution of the population of young cod, possibly due to high temperatures through several years before and including 1976 (Loeng, 1989; Nakken and Raknes, 1984; Midttun and Loeng, 1987).

From 1977 to 1982 the temperatures of the Barents Sea were low (Midttun and Loeng, *op.cit.*), which is probably the reason for the displacement of the cod stock further west and south. The influence on the fisheries is very clear from the cod fishing maps from 1981 (Fig. 9, bottom). In the winter months of that year (Fig. 9, bottom left) the Norwegian cod catches were very low east of the Varanger Peninsula and further to the north. Even in the autumn months of that year the catches were concentrated relatively close to the coast of northern Troms and Finnmark (Fig. 9, bottom right). The sea temperatures in the Barents Sea strongly increased again for a couple of years from 1982 (Midttun and Loeng, *op.cit.*). From the above mentioned observations on temperatures in relation to the cod stocks, higher catches might be expected further to the east, at least from autumn 1984, but this seems not to be the case (Fig. 10, top). The reason may be that the larger cod are by then used to a southwesterly distribution from their "youth" stages at the low temperatures existing in the Barents Sea before 1982 (Hylen *et al.*, 1985). For the Norwegian late-summer cod fisheries there was an important area from 1983 onwards at "Sørbakken", south of Bear Island (upper right map in Fig. 10). The basis was possibly fish of the Bear Island stock "drifting" southwards, but may also be westerly fish of the Barents Sea population.

There is a good correspondence between the Norwegian late summer cod fishery map 1984 and the cod and haddock resources calculated in terms of weight from the echo integrator values per squared nautical mile (Fig. 10 right, top and bottom, respectively). The only significant deviation relates to the resource maximum shown at about 74°N and 32°E. This maximum, however, may be young fish, too small for fishing, easterly distributed during the period of high temperatures in 1982–1983 and partly in 1984. The same reason may be suggested for the resource maxima of cod and haddock in the north and east in January–April 1985 (Fig. 10, lower left), and also observed in the northeast for the same period of 1986.

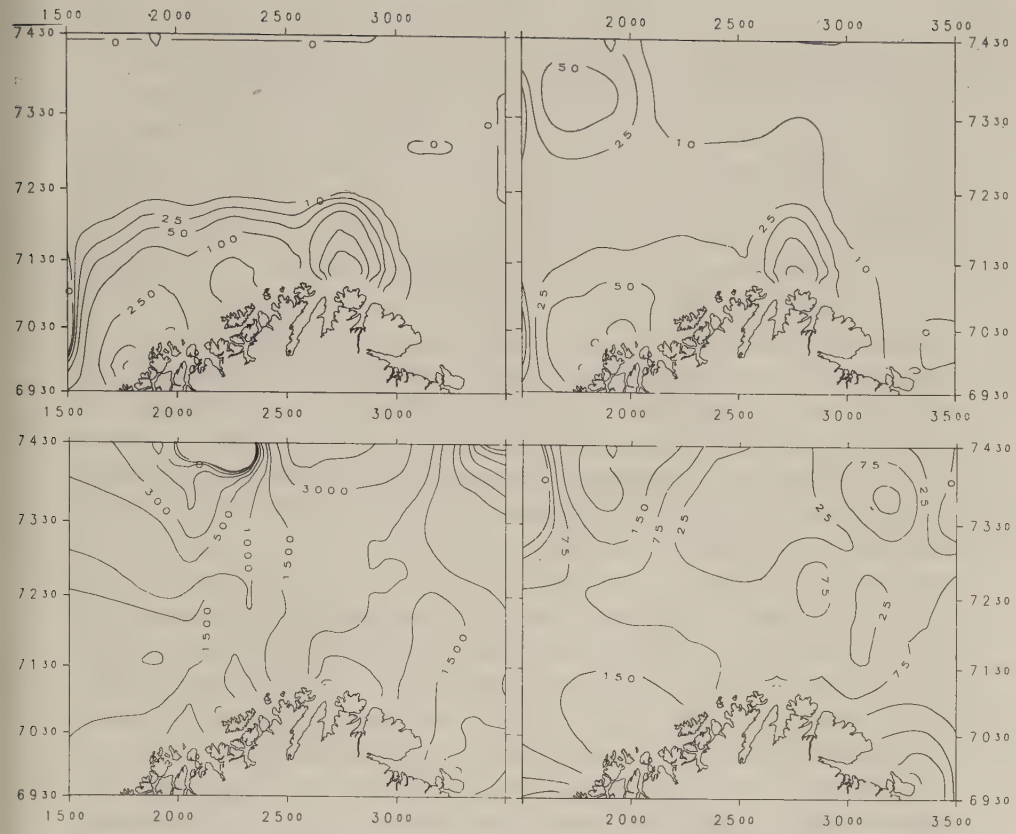

Fig. 10 Isolines (in 10 kg per square nautical mile) for the catches in the cod fisheries (upper part) and the resources of cod and haddock (lower part) in the southern part of the Barents Sea. Left, January–April 1985. Right, September–December 1984.

For all years studied, the cod fisheries in the southern Barents Sea were lower in the period September–December than in January–April. This was the case also for the amount of resources, but the great differences between the two periods (lower part of Fig. 10) are probably partly due to fewer bottom-trawl surveys during the autumn than during the winter.

FISH MIGRATION

1) *General*

Although fish in the Barents Sea generally migrate in a southwesterly direction before spawning in winter, and migrate northeastwards for food during summer, variations in temperatures may cause changes in the speed and direction of the migration. The real "preference" temperature for the actual fish species is not known, but if temperature is to drive the migration in a specific direction it has to be higher during periods of southwards migration

than during periods of northwards migration. It may be expected that mature fish during spawning are most sensitive to environmental conditions such as salinity and temperature (Dragesund and Gjøsæter, 1988), and may then also prefer higher temperatures. This is common in terrestrial animals during sexual reproduction, but the preferences under spawning migration of fish may be less clear.

The mean sea temperatures of the Barents Sea at 50–200 m depth for the years 1984–1987 (Fig. 6, top) show that the values in May, for instance, vary from about 3°C to nearly 4.5°C in areas with the highest densities of spawning capelin near the Finnmark coast. This means that the temperature preferred by spawning capelin probably is somewhere in that interval. The preferred "feeding migration" temperatures have to be lower than about 3°C if temperature is a northwards migration driving force for capelin. However, even in late summer, the average temperatures at 50–200 m depth are in many years not below 0°C, even relatively far north. Therefore, the preferred temperatures for "feeding migration" in capelin are probably between 3°C and 0°C.

Cod and haddock may prefer somewhat higher temperatures than capelin. The main spawning area for Arctic cod is the Lofoten- Vesterålen area. In January–April, the most important spawning period, the mean temperature at 50–200 m depth may be nearly 7°C in that district. However, some cod and generally haddock, may spawn somewhat further north. Outside western Finnmark the main winter temperatures may go down to nearly 4°C. This means that the spawning temperatures for these species are to be found between the extremes mentioned. The "feeding migration" temperatures for the same species again may be expected to be somewhat lower, because of the general northward summer migration. In summer, high densities of cod and haddock may be found on the bank areas in the Barents Sea with sea temperatures from above 1.5°C to about 5.5°C at 50–200 m depth, probably with the oldest fish at the highest temperatures.

2) *Capelin*

a) Spawning migration

Capelin spawning is most intense during March–April, but may start already in February, and conclude as late as July (Bjørke *et al.*, 1982). Tjelmeland (1987) says that capelin starting the spawning migration late in the season is generally influenced by low temperatures. He therefore postulates that the late-migrating fish have a more westerly migration route in an attempt to find higher temperatures. Russian scientists have also shown a good correlation between the spawning migration of capelin and temperature (Ozhigin and Luka, 1985). They found that in years with high sea temperatures most

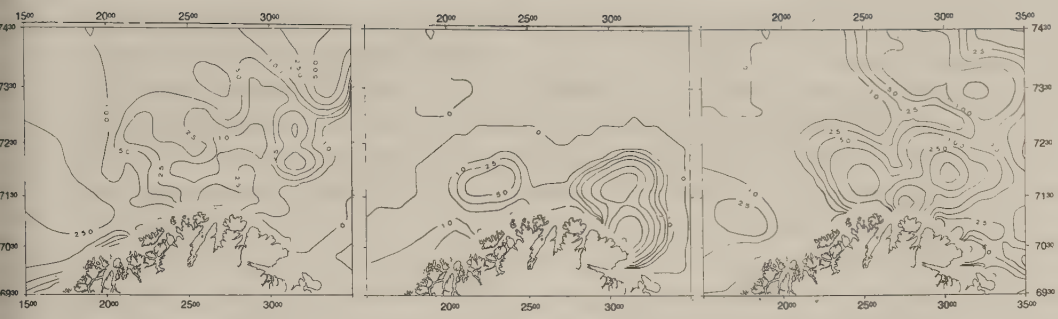

Fig. 11 Spawning migration of capelin in the southern Barents Sea, winter 1985. Left, resources in February. Middle, model prediction of resources 89 days after February, assuming the "preference" temperature 3.5°C. Right, observed resources in May same year.

of the spawning takes place near the coast of the eastern Kola Peninsula, and very little west of the North Cape. In colder years, however, they observed very little spawning east of the Varanger Fjord. These observations show that even capelin, normally living far north in the Barents Sea, may be dependent on the temperature during the spawning period. In the first year of the present study, a year with relatively high sea temperatures, the main spawning stocks of capelin were observed north of the Varanger Peninsula, while somewhat further west (north of Nordkyn) in later years with a lower sea temperature.

In the migration model various "preference" temperatures have been experimentally tried within the probable range of values given above. For modelling spawning migration of capelin, it generally seems that 3.5°C is the best fitted value. By using higher temperatures, the concentration of capelin is predicted by the model to be further west after spawning migration than was observed, and by using lower temperatures, further east. The observed spawning migration, however, seems to be slower towards the coast than that modelled. In February, and also to some extent in May 1985, considerable amounts of capelin were still observed at about 73°30′N and 32°E (Fig. 11, left and right). The model, with 3.5°C "preference" temperature, shows a considerably stronger southward migration during this period (Fig. 11 middle). On the other hand, survey data from April and May 1985 show a strong southwards migration during early May. This indicates that the spawning migration of capelin might be very rapid, in this case passing 2° or more southwards (Wielgolaski, 1988), probably in less than one month.

b) "Feeding migration"

Because most of the capelin die after spawning, only very few mature capelin migrate for food during summer and early autumn. Only immature capelin, therefore, are indicated on the "feeding migration" maps (Fig. 12).

In May 1985 the geographical distribution of the immature stock of capelin was similar to that of the mature fish (Fig. 11 right), but the immature stock is more than twice as abundant as the mature capelin. The reason for the similarity of this picture for late winter is that the immature fish often follow the adults part of the way on their spawning migration. From June and through the summer the normal "feeding migration" is northeastwards. For the geographical area pictured to the right in Fig. 12, nearly all the capelin in September 1985 is concentrated north of the map, according to survey observations. Different temperatures are used in the model to find the best value for the northeastward migration in summer. In Fig. 12 to the left, an example is given with "preference" temperature 3.5°C for migration from June to September 1985, but this temperature obviously is too high to drive the stock northwards during summer.

Using the 1985 "feeding migration" period as an example, 0°C was the best fitted "preference" temperature in the model. However, the use of 1°C seems to describe the general situation better, for instance, during the summer period of 1984. Then more fish are observed to be in the southern Barents Sea, at least by August, than in 1985. In years with a higher stock size and a "normal" age distribution of the capelin, the youngest age classes (0 and 1 year) are observed to migrate least to the north during summer, because of a need for higher temperatures (Hamre and Tjelmeland, 1982). The modelled migration shown in the middle of Fig. 12, by use of 1°C as the "preference" temperature, may give the picture in a "normal" year. In 1985, however, the youngest age classes were very small, which may imply that older capelin, migrating further to the north, dominated the stock. A different picture of the summer migration seemed to be the case in August–September 1986. Then there was only a small stock left, even of "older"

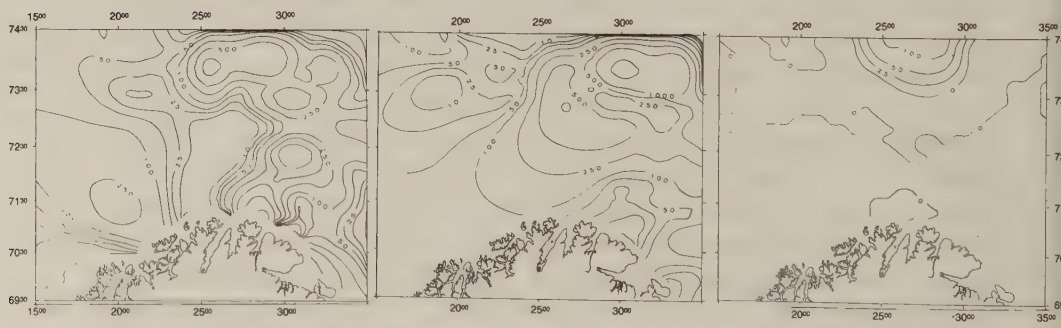

Fig. 12. "Feeding migration" of immature capelin in the southern Barents Sea, summer 1985. Left, modelling result for migration 123 days from May, assuming the "preference" temperature 3.5°C. Middle, same, but at the temperature 1°C. Right, observed resources in September same year.

immature capelin, and therefore, small stocks were observed also in more northern areas of the Barents Sea.

Both for the capelin spawning migration and the "feeding migration", deviations from "normal" temperatures are used in the model to verify its possible use in a predictive way. The model proved to be less realistic when the migration was simulated four months or more into the future than at shorter intervals.

3) *Cod/haddock*

a) Spawning migration

Already in early winter, when the sea temperatures begin to decrease (Fig. 2), cod and haddock starts to migrate to the spawning grounds. In December and January the mature fish generally is found in schools at the depth of 200–400 m along western Finnmark. In the model the highest migration rate to the main spawning grounds (to the Lofoten- Vesterålen area for cod and to the continental shelf outside the northernmost Norwegian counties for haddock) is said to be in February–March. After spawning, according to the model generally in March and the first part of April, most of the cod and haddock have survived and migrate northwards again for feeding.

The spawning migration is simulated in the model for various "preference" temperatures between the values 4° and 7°C, which were observed in the actual areas during the period of study. As a compromise, the temperature 5.5°C or slightly less, seemed to offer the best approach for the cod and haddock spawning migration. With this "preference" temperature a great part of the 1985 spawning stock was predicted to be still at about 70°30′N and 17°E after two months of southwards migration from February (Fig. 13, upper right), although most of the cod is expected to be south of 69°30′ at that time. However, the southwesterly maxima shown on the map is probably within the most important spawning grounds for haddock, but the larger part of the stock was expected to be cod. Another possibility for the northerly distribution modelled in April 1985 after two months of southwards migration is that not all of the mature fish had yet migrated to the spawning grounds. This is confirmed by survey maps from April (for instance in 1985, Fig. 13, lower right) and May in various years. In May the observed stocks were generally concentrated further south than in April. In the present version of the model, however, it is supposed that so much of the spawning is finished in March, that in April the general direction of migration is already towards the northeast.

As for capelin, the migration model for cod and haddock may be used in a predictive way by assuming that deviations from a "normal" temperature will be the same in the future. This seems to be valid at least for a period

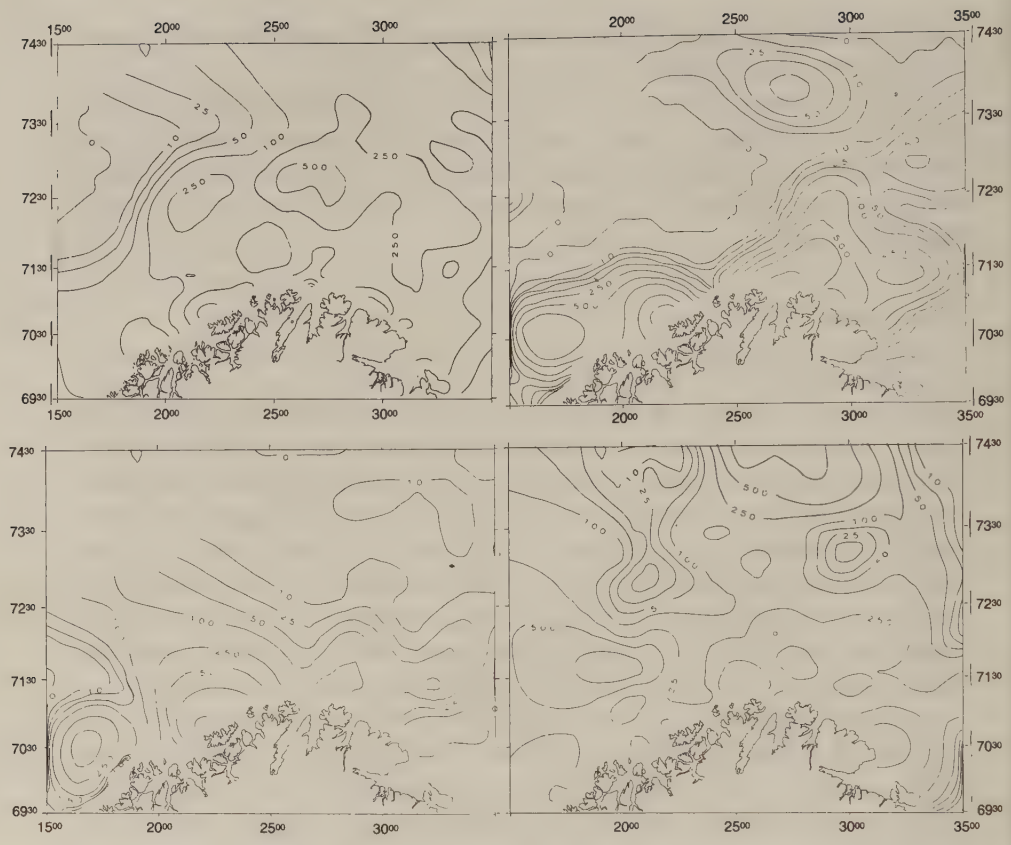

Fig. 13. Spawning migration of cod and haddock in the southern Barents Sea, winter 1985. Upper left, resources in February. Upper right, modelling result for migration 59 days from February in one step at the "preference" temperature 5.5°C. Lower left, same but the migration is carried out in two steps in the model. Lower right, resources in April same year.

of two months. For longer periods the deviation may be too large for the model to simulate the situation satisfactorily.

b) "Feeding migration"

After hatching, the fry of cod and haddock drift northeastwards with the upper-layer sea current far into the Barents Sea. The youngest fish is found in the eastern part of the distribution area (Midttun *et al.*, 1981; Hylen *et al.*, 1985), where the temperatures generally are lower than further to the west at the same latitude (examples in Fig. 6).

Various "preference" temperatures are provisionally applied in the model for simulating the "feeding migration" for immature cod and haddock. It was observed that a temperature of 1.5°C resulted in a too rapid northeast-

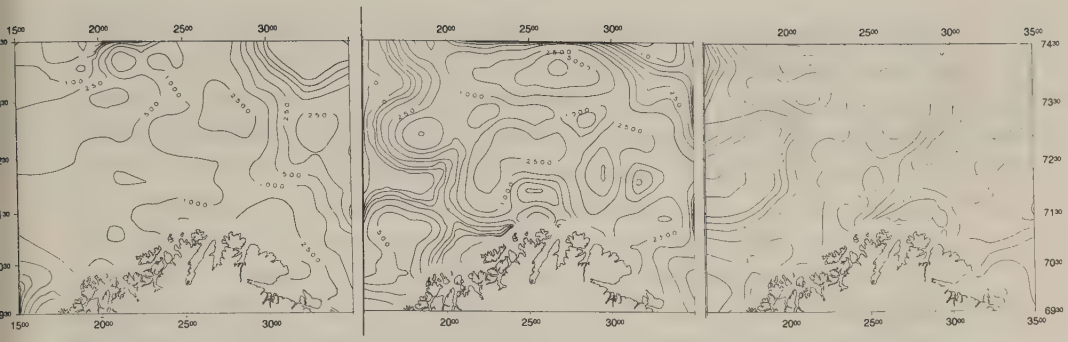

Fig. 14. "Feeding migration" of immature cod and haddock in the southern Barents Sea, summer 1985. Left, resources in May. Middle, modelling result for migration 153 days from May in one step at the "preference" temperature 3.0°C. Right, resources in October same year.

wards migration. However, too much fish was left near the coast of northern Norway if a "preference" temperature of 4.5°C was used. The best compromise temperature for the northeastward summer migration of young cod and haddock seems to be 3.0°C. With this "preference" temperature the majority of the immature fish is modelled to be in the same areas as observed during surveys (Fig. 14, middle and right). However, more of the fish is predicted to be left in the southwest of the mapped area than observed, and locally some of the fish aggregations are too dense, as compared to their real distribution. Consequently, too high densities are modelled for some areas (Fig. 14).

Mature cod and haddock are found to stop their northeastward migration further to the southwest than do younger fishes (Rollefsen and Hylen, 1981), indicating that a higher temperature is preferred by the mature fish. In the model 5.5°C seems to satisfy as a "preference" temperature for their "feeding migration". This temperature gives a slow and short migration of the fish as the temperature slowly increases during the summer.

The simulated "feeding migrations" of immature cod and haddock seem to be better related to the survey data of the stock when based on the observed temperatures. However, again the deviations in temperatures from a "normal" state at the beginning of a period may be used in a predictive way, at least for a period of a couple of months.

CONCLUSION

In spite of many weaknesses in the present model, for example, those due to too few detailed data on the geographical distribution of prey organisms, the present model may be useful for predicting the migrations of capelin and cod and haddock two to three months ahead of the last survey. This might be valuable, for instance, in anticipating the contact between fish stocks and a possible oil slick in the Barents Sea.

In the winter, in certain areas, a large oil spill may cause the fish to stop or change their spawning migration to escape the spill, thus reaching less favourable spawning grounds (Wielgolaski, 1987). The result may be a reduced year class, which also will influence the spawning stock for several years in the future. Even more damage may be done if oil drifts towards the spawning grounds, when vulnerable eggs and young larvae are present in the surface layers (Føyn and Serigstad 1987; Serigstad *et al.*, 1987). Larger fish during "feeding migration" are probably less directly influenced by oil spills. They will normally try to escape the oil because of the smell, down to oil concentrations of 0.1 ppb (Wielgolaski, 1989). The amount of food organisms may, however, be influenced. Particularly eggs and young zooplankton are known to be sensitive to oil pollution (Melle and Skjoldal, 1987).

Fish growth is influenced both by the available amounts of food and by physical factors, for instance temperature. The sexual maturity process in capelin and cod, among other species, is dependent not only on the age but also on the growth rate. Reduced food availability, as because of large oil spills over large areas, may thus delay maturing and indirectly reduce the fish stock.

The model unfortunately treats the geographical distribution of plankton in only a limited fashion. There are simply too few quantitative data available on the various size groups of plankton by area and time to allow for the construction of a useful plankton migration model. The empirical knowledge of fish distribution used in the model indirectly reflects the plankton distribution, as several groups of these organisms are the main food source for fish. This is easily seen for plankton feeders such as capelin. Cod and haddock may be less dependent on the plankton distribution as planktonic organisms seem to be their most important diet only in certain periods. Generally, however, demersal fish are very dependent on plankton-feeding fish, and thus indirectly also depend on the plankton distribution. Unpublished studies (Mehl, pers. comm.) indicate that cod also feed on larger planktonic organisms, for instance, on amphipods, at least when capelin stocks are at reduced levels in September–October. Therefore, it is very important to collect as detailed information as possible on the various plankton groups. Reduced amounts of pelagic fish in the sea seem to cause very strong cannibalism in demersal fish such as cod, and illustrate the importance of collecting fish stomach data to see the qualitative and quantitative food intake by various fish species (Mehl and Tjelmeland, 1988). There are, of course, also important feedback mechanisms from the amount of fish to the amount of plankton in the various parts of the Barents Sea, which again will strongly influence the ecosystem.

It is not possible to make a really good quantitative ecosystem and fish-migration model for the Barents Sea before detailed plankton distribution

data and stomach content data are available, in addition to good data on fish resources and their distribution. Eventually such models will be of the greatest importance both for management of the various fish populations within the region and for prediction of the environmental impact of a possible oil spill disaster in the Barents Sea.

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REFERENCES

Bjørke, H., Hassel, A., Loeng, H. and Rey, F. 1982. Fiskeressursene og deres miljø i Barentshavet, ved Svalbard og ved Jan Mayen (Fish resources and their environment in the Barents Sea, near Svalbard and Jan Mayen, in Norwegian). Bergen: Fiskeridirektoratets Havforskningsinstitutt (Institute of Marine Research), Manuscript. 52 pp.

Bliznichenko, T.E., Degtereva, A.A., Drobysheva, S.S., Nesterova, V.N., Plekhanova, N.V. and Ryzhov, V.M. 1984. Plankton investigations in the Norwegian and Barents Sea. *Annales Biologiques 38*: 71–73.

Børresen, J.A., Christie, H. and Aaserød, M.I. 1988. Opening of the Barents Sea South, Troms II, Troms III and the southern part of Finnmark West for petroleum activities. Environmental impact statement (In Norwegian with English summary). Oslo: Norw. Ministry of Oil and Energy. 90 pp.

Dalen, J. and Smedstad, O.M. 1983. Abundance estimation of demersal fish in the Barents Sea by an extended acoustic method, 232– 293. In: *Symposium on Fisheries Acoustics, Bergen, Norway*. Rome: FAO. 331 pp.

Degtereva, A.A., Drobysheva, S.S., Nesterova, V.N., Plekhanova, N.V. and Ryzhov, V.M. 1986. Results of plankton investigations in the Norwegian and Barents Seas in 1984. *Annales Biologiques 41*: 69–71.

Dommasnes, A., and Røttingen, I. 1985. Acoustic stock measurements of the Barents Sea Capelin, 45–108. In: Gjøsæter, H. ed.: *Proc. Soviet-Norwegian Symposium on the Barents Sea Capelin, Bergen, Norway*. Bergen: Institute of Marine Research. 236 pp.

Dragesund, O. and Gjøsæter, J. 1988. The Barents Sea, 339–361. In: Postma, H. and Zijlstra, J.J. eds.: *Continental Shelves*. Ecosystems of the World vol. 27. Amsterdam: Elsevier.

Drobysheva, S.S., Nesvetova, G.I., Nesterova, V.N., Ryzhov, V.M. and Chepurnov, A.N. 1988. Division of the Barents Sea in view of primary and plankton production formation type, 1–20. *ICES, CM 1988/L*:7.

Ellertsen, B., Hassel, A., Loeng, H., Rey, F., Tjelmeland, S. and Slagstad, D. 1982. Økologiske undersøkelser nær iskanten i Barentshavet somrene 1979 og 1980 (Ecological studies near the ice edge in the Barents Sea during the summers 1979 and 1980, in Norwegian). 31–83. In: *Fisken Hav., 1982*, No.3.

FOH 1983. Research Projects 1977–83. The Norwegian Marine Pollution Research and Monitoring Programme. Oslo: Norw. Ministry of Environment. 91 pp.

FOH 1984. Oljens skjebne og effekter i havet (Fate and effects of oil in the sea, in Norwegian). Oslo: Miljøverndepartementet (Norw. Ministry of Environment). 75 pp.

Føyn, L. In preparation. Konsekvenser av mulig oljevirksomhet i Barentshavet Syd m.v. på det marine miljø, med særlig vekt på utnytting av fiskeressurser (Impacts of possible oil spill in the Barents Sea South etc on the marine environment, particularly on the use of fish resources, in Norwegian). Bergen: Havforskningsinstituttet (Institute of Marine Research).

Føyn, L. and Serigstad, B. 1987. Age dependent sensitivity of oil on fish larvae, used in assessment of potential oil pollution damages on fish resources, 1–15. *ICES, CM 1987/E*: 12.

Hamre, J. and Tjelmeland, S. 1982. Sustainable yield estimates of the Barents Sea capelin stock, 1–25. *ICES, CM 1982/H*: 45.

Hylen, A., Jakobsen, T., Nakken, O. and Sunnanå, K. 1985. Preliminary report of the Norwegian investigations on young cod and haddock in the Barents Sea during winter 1985. 1–28. *ICES, CM 1985/G*: 68.

ICES 1979–1989. Nominal catch (tonnes) of various species of fish, invertebrates and seaweeds taken by member countries in the ICES statistical area. Table 5 in *Bulletin Statistique des Peches Maritimes*. Vols. 61–71.

Lindseth, O.A. 1987. Petroleumsvirksomheten i nordområdene (The petroleum exploration in the north, in Norwegian). *Esso Perspektiv 29*, No. 4: 3–4.

Loeng, H. 1989. Ecological features of the Barents Sea, 327–365. In: Rey, F. and Alexander, V. eds.: *Proc. 6th. Conf. Comité Arctique Int., Fairbanks 1985*. Leiden: E.J. Brill. 635 pp.

Mehl, S. and Tjelmeland, S. 1988. Sluttrapport til Norges Fiskeriforskningsråd frå prosjekt I 701.115 Fleirbestandsmodell for Barentshavet (Final report NFFR from the project I 701.115 A multiple species model for the Barents Sea, in Norwegian). Bergen: Fiskeridirektoratets Havforskningsinstitutt (Institute of Marine Research), *Report FB 8801*. 6 pp.

Melle, W. and Skjoldal, H.R. 1987. Dyreplankton og dets reproduksjon i Barentshavet – Grunnlagsmateriale for vurdering av mulige skader av oljesøl. Foreløpig rapport (Zooplankton and the reproduction in the Barents Sea – Base material for evaluation of possible oil spill effects. Preliminary report, in Norwegian). Bergen: Fiskeridirektoratets Havforskningsinstitutt institutt (Institute of Marine Research), *Report BKO 8707*. 41 pp.

Midttun, L., Nakken, O. and Raknes, A. 1981. Variasjoner i utbredelsen av torsk i Barentshavet i perioden 1977–1981 (Variation in the distribution of cod in the Barents Sea in the period 1977-1981, in Norwegian). 1–16. *Fisken Hav., 1981*, No. 4.

Midttun, L. and Loeng, H. 1987. Climatic variations in the Barents Sea, 13–27. In: Loeng, H., ed.: *Proc. 3rd Soviet-Norwegian Symposium, Murmansk, USSR on the Effect of Oceanographic Conditions on Distribution and Population Dynamics of Commercial Fish Stocks in the Barents Sea*. Bergen: Institute of Marine Research. 250 pp.

Nakken, O. and Raknes, A. 1984. On the geographical distribution of Arctic cod in relation to the distribution of bottom temperature in the Barents Sea, 1977–1984, 1–17. *ICES, CM 1984/GM*: 20.

Oppedal,G. 1987. Fangstdata Barentshavet Syd (Catch data for the Barents Sea South, in Norwegian). Bergen: Fiskeridirektoratet (The Directorate of Fisheries) *AKUP document No. 040101.* 95 pp + 3 appendices.

Ozhigin,V.K. and Luka, G.I. 1985. Some pecularities of capelin migrations depending on thermal conditions in the Barents Sea, 135–147. In: Gjøsæter, H. ed.: *Proc. Soviet-Norwegian Symposium on the Barents Sea Capelin, Bergen, Norway.* Bergen: Institute of Marine Research. 236 pp.

Rey, F. and Loeng, H. 1985. The influence of ice and hydrographic conditions on the development of phytoplankton in the Barents Sea, 49–63. In: Gray, J. S. and Christiansen, M. E. eds.: *Marine Biology of Polar Regions and Effects of Stress on Marine Organisms.* London: John Wiley & Sons Ltd. 639 pp.

Rey, F., Skjoldal, H.R. and Hassel, A. 1987a. Seasonal development of plankton in the Barents Sea: A conceptional model, 1–36. *ICES 1987/Symp:* 56.

Rey. F., Skjoldal, H.R. and Slagstad, D. 1987b. Primary production in relation to climatic changes in the Barents Sea, 29–46. In: Loeng, H. ed.: *Proc. 3rd Soviet-Norwegian Symposium, Murmansk, USSR on the Effect of Oceanographic Conditions on Distribution and Population Dynamics of Commercial Fish Stocks in the Barents Sea.* Bergen: Institute of Marine Research. 250 pp.

Rollefsen, G. and Hylen, A. 1981. Torsken (The Cod, in Norwegian). *Norges Dyr (Norwegian Animals) Vol. 3.* Oslo: Cappelen Forlag. 408 pp.

Serigstad, B., Føyn. L. and Ellingsen, T. 1987. Fiskelarvenes følsomhet for olje som funksjon av alder. Foreløpig rapport. (The sensitivity of fish larvae for pollution as a function of age. Preliminary report, in Norwegian). Bergen: Fiskeridirektoratets Havforskningsinstitutt (Institute of Marine Research), *Report BKO 8706.* 21 pp. + 1 appendix.

Skjoldal, H. R., Hassel, A., Rey, F. and Loeng, H. 1987. Spring phytoplankton and zooplankton reproduction in the central Barents Sea in the period 1979-1984, 59–89. In: Loeng, H. ed.: *Proc. 3rd Soviet-Norwegian Symposium, Murmansk, USSR on the Effect of Oceanographic Conditions of Distribution and Population Dynamics of Commercial Fish Stocks in the Barents Sea.* Bergen: Institute of Marine Research. 250 pp.

Tjelmeland, S. 1987. The effect of ambient temperature on the spawning migration of capelin, 225–236. In: Loeng, H. ed.: *Proc. 3rd Soviet-Norwegian Symposium, Murmansk, USSR on the Effect of Oceanographic Conditions on Distribution and Population Dynamics of Commercial Fish Stocks in the Barents Sea.* Bergen: Institute of Marine Research. 250 pp.

Westgård, T., Knutsen, T. and Christiansen, A. 1988. Users guide, Map-Library, version 1, August 1988. Bergen: *Havforskningsinstituttets Egg- og larveprogram, (Institute of Marine Research, The egg- and larval program), Report 18.* 132 pp.

Wielgolaski, F.E. 1987. Konsekvensutredninger for Barentshavet Syd m.v. Kartlegging og systematisering av fiskefordelingen. Foreløpig rapport. (Environmental impact analyses for the Barents Sea South etc. Mapping and migration of the fish resources. Preliminary report, in Norwegian). Bergen: Fiskeridirektoratets Havforskningsinstitutt (Institute of Marine Research), *Report BKO 8705.* 42 pp. + 6 appendices.

Wielgolaski, F.E. 1988. Konsekvensutredninger for Barentshavet Syd m.v. Kartlegging og systematisering av fiskefordelingen. Sluttrapport. (Environmental impact analyses for the Barents Sea South etc. Mapping and migration of fish resources. Final report, in Norwegian). Bergen: Fiskeridirektoratets Havforskningsinstitutt, (Institute of Marine Research), *Report BKO 8901.* 57 pp. + 12 appendices.

Wielgolaski, F.E. 1989. Oil spills in the Barents Sea, 115–131. In: Öztürk, M. A., et al. eds: *Plants and Pollutants in Developed and Developing Countries.* Izmir, Turkey. Ege Univ. Press. 760 pp.

Zenkevitch, L. 1963. *Biology of the Seas of the USSR.* London: George Allen & Unwin Ltd. 955 pp.

CONTENTS

F.E. Wielgolaski. A Barents Sea fish resources and migration model, developed with special reference to oil activity 381–409

A.S JOHN GRIEG